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# Numerical simulation of in situ production of cosmogenic nuclides: Effects of irradiation geometry

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## Abstract

A variety of geomorphic events and processes can be studied with the cosmogenic nuclides accumulated in the exposed materials. Reliable interpretation of the measured in situ produced cosmogenic nuclides requires a good understanding of the involved nuclear processes. The production rates of nuclides depend on many parameters. In this paper, calculations for the production rates of in situ produced cosmogenic nuclides in rocks of various sizes on sloped surfaces are reported and discussed. © 2000 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The interactions of cosmic-ray particles with the Earth's atmosphere produce a cascade of secondary particles and many cosmogenic nuclides. Many secondaries have enough energy to undergo further collisions and to give rise to the next generation of secondary particles. Some of the particles from this cascade can reach the Earth's surface and induce nuclear reactions in which a variety of cosmogenic nuclides are produced. The cosmogenic-nuclide concentration in a terrestrial sample depends on the sample's composition, altitude, geomagnetic latitude, and exposure geometry and their changes with the time.

While the cosmogenic-nuclide method was being developed, most samples were obtained from horizontal flat surfaces and from large boulders. To make this method a common universal analytical tool, it must be applicable in much broader range of sampling site geometries. The goal of this paper is to investigate the effects of size of the sampled object and of shielding by depth on a sloped surface. We present a pure physical model approach to this problem. Similar studies employing some approximations and simplifications were published earlier [1].

## 2. Model calculations

Our model for the simulation of the interaction of primary and secondary cosmic ray particles

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with matter is based on the GEANT [2] and MCNP [3] codes. As this code system is described in detail elsewhere [4], we repeat here only its main features that are relevant for the present study.

In our simulations, only primary protons with energies between 10 MeV and 100 GeV were considered. The characteristic feature of the particle interactions at these energies is the production of the cascade of secondary particles. For these calculations the Earth's atmosphere was modeled as a spherical shell with an inner radius of 6378 km and a thickness of 100 km. The following elemental composition (in wt%) was used: 75.5% N, 23.2% O and 1.3% Ar. The total thickness of the atmosphere was 1033 g cm<sup>-2</sup>. The elemental composition of the surface was assumed to be an average terrestrial one (in wt%, 0.2% H, 47.3% O, 2.5% Na, 4.0% Mg, 6.0% Al, 29.0% Si, 5.0% Ca and 6.0% Fe). Except for very high contents of H, changes in this surface composition, or the addition of other elements such as K, have very little effect on the calculated fluxes. The surface density of the Earth was 2.0 g cm<sup>-3</sup>. To investigate the depth dependence of particle fluxes, the sphere near the surface was divided into spherical shells with thickness of 5 g cm<sup>-2</sup>. The fluxes of protons and neutrons within each cell were calculated.

The production rate of a cosmogenic nuclide  $j$  at depth  $d$  is

$$P_j(d, M) = \sum_i N_i \int_0^\infty \sigma_{ijk}(E_k) J_k(E_k, d, M) dE_k, \quad (1)$$

where  $N_i$  is the number of atoms for target element  $i$  per kg material in the sample,  $\sigma_{ijk}(E_k)$  is the cross section for the production of the cosmogenic nuclide  $j$  from the target element  $i$  by particles of type  $k$  with energy  $E_k$ , and  $J_k(E_k, d, M)$  is the flux of particles of type  $k$  with energy  $E_k$  at depth  $d$  inside the Earth's atmosphere and solar intensity characterized by modulation parameter  $M$ . The particle fluxes  $J_k(E_k, d, M)$  were calculated with the GEANT/MCNP code system. The statistical errors of the calculations were on the level of 5–8%. The systematic uncertainties of our calculated fluxes are estimated to be in the range of 5–10% for depths less than 400 g cm<sup>-2</sup> and increase with depth under the Earth's surface. For the cross

sections  $\sigma_{ijk}(E)$  we relied on the values evaluated and tested in earlier calculations [5,6] and updated with new values from recent experiments [7–10].

In this paper, we present only the production rates originating from the interactions of galactic cosmic rays. Their fluxes vary in time. The dominant sources of the variations are the solar and geomagnetic modulation. The solar modulation is taken into account in the expression for the differential primary GCR proton flux [11]. Solar cosmic ray particles produce cosmogenic nuclides only at shallow depths in the atmosphere and only at high latitude, where the geomagnetic field does not prevent them from entering the atmosphere [4,6]. The integral flux of primary cosmic ray protons with energies above 10 MeV used in these simulations is 4.56 nucleons cm<sup>-2</sup> s<sup>-1</sup>. This value corresponds to the modulation parameter  $\phi = 550$  MeV, which is identical with the long-term average value, determined from cosmogenic nuclide data in lunar samples [6].

### 3. Results and discussion

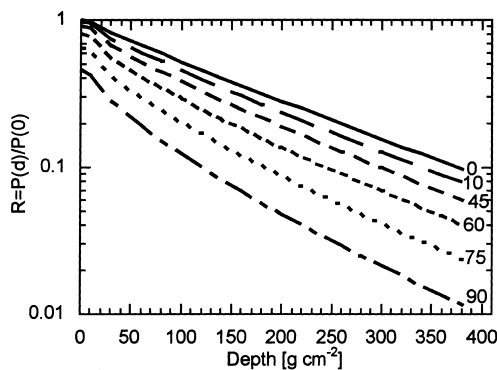
The dependence of the production rate on the slope of the sample location has its origin in non-isotropic flux of particles producing given nuclide. The particle flux as the function of azimuth angle  $\theta$  is usually described by  $\cos^n \theta$ . The values of  $n$  range from 2.3 to 3.5 [12–15]. Fit to our calculated fluxes gives the value of  $n = 2.65$ . The absorption mean free path  $\Lambda$  changes with the slope because of the change of number of particles effectively involved in the production of nuclides at given depth. The dependence of the production rate on slope cannot be obtained in analytical form, as in the case of flat horizontal geometry [1], but has to be done numerically. In our model, the production rate at different depth under the Earth's surface of different slopes was calculated directly from expression (1). The results of the calculations for <sup>10</sup>Be are given in Table 1.

Calculated dependencies of the production rates on the depth  $d$  (g cm<sup>-2</sup>) and slope angles  $\Lambda$  (°) (Fig. 1) at the depth below 10 g cm<sup>-2</sup> can be fitted by

Table 1

Production rates of  $^{10}\text{Be}$  on a sloped surface as function of depth under the surface relative to 0-cm depth and flat horizontal surface

Depth $d$ ( $\text{g cm}^{-2}$ )	Azimuth angle ( $^\circ$ )					
	0	10	45	60	75	90
1	1.00	0.968	0.909	0.795	0.649	0.459
10	0.984	0.958	0.893	0.778	0.626	0.428
30	0.818	0.755	0.670	0.553	0.416	0.285
60	0.673	0.603	0.520	0.413	0.299	0.193
80	0.592	0.523	0.444	0.346	0.245	0.153
100	0.522	0.456	0.382	0.293	0.203	0.124
120	0.461	0.398	0.330	0.249	0.170	0.101
140	0.407	0.349	0.286	0.213	0.143	0.0829
160	0.360	0.306	0.249	0.183	0.121	0.0688
180	0.319	0.269	0.217	0.158	0.103	0.0574
200	0.283	0.237	0.190	0.137	0.0877	0.0482
220	0.251	0.209	0.166	0.119	0.0751	0.0407
240	0.223	0.185	0.146	0.103	0.0645	0.0344
260	0.198	0.163	0.128	0.0899	0.0555	0.0293
280	0.176	0.145	0.113	0.0785	0.0480	0.0249
300	0.157	0.128	0.0993	0.0686	0.0415	0.0213
320	0.139	0.114	0.0876	0.0601	0.0360	0.0183
340	0.124	0.101	0.0772	0.0527	0.0312	0.0157
360	0.111	0.0896	0.0684	0.0463	0.0272	0.0135
380	0.0987	0.0796	0.0605	0.0407	0.0237	0.0116

Fig. 1. Relative production rates of  $^{10}\text{Be}$  on a sloped surface as function of depth under the surface for azimuth angles  $0^\circ$ ,  $10^\circ$ ,  $45^\circ$ ,  $60^\circ$ ,  $75^\circ$  and  $90^\circ$ .

$$P = aP_0 e^{-d/\Lambda},$$

where the values for parameters  $a$  and  $\Lambda$  are in Table 2. This function with corresponding parameters can be used for the determination of production rate for any slope and depth in the sample location. Within the statistical errors of

Table 2

Coefficients of exponential fit describing the dependence of  $^{10}\text{Be}$  production rate on depth and surface slope

Azimuth angle ( $^\circ$ )	$a$	$\Lambda$ ( $\text{g cm}^{-2}$ )
0	1.000	164.7
10	0.968	153.8
45	0.909	143.1
60	0.795	131.2
75	0.649	118.9
90	0.459	95.3

calculations it is valid for all nuclides produced in spallogenic reactions. Near the surface, at depths smaller than  $10 \text{ g cm}^{-2}$  the production rate shows flat profile or very slow decrease [6].

Many of the experimentally studied samples were taken from the big boulders. We studied the influence of size of the sampling rock on the observed production rates using our model. In our case the boulder was simulated as a hemisphere with radius varying from 30 to 300 cm. We carried out simulations of production rates for two

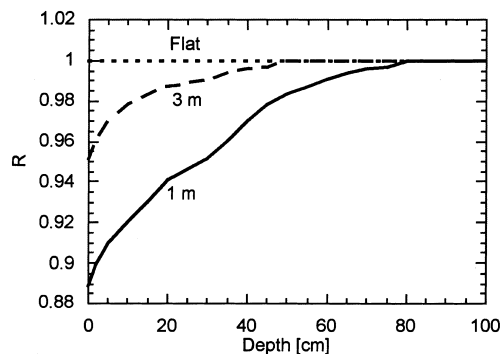


Fig. 2. Ratio of production rate of  $^{10}\text{Be}$  in hemisphere with radius 3 and 1 m and in flat horizontal surface.

different cases. In the first case, the whole object was divided into hemispheric layers and the production rate in every layer was calculated. In the second case, the production rates were calculated as function of the depth in the cylinder with radius 2.5 cm, the axis of which was perpendicular to the Earth's surface and passed through the center of the hemisphere. (This geometry was aimed to represent core drilling in boulders.)

As an example, we present the results of calculations of ratio of production rate of  $^{10}\text{Be}$  in hemisphere with radius 3 and 1 m and in flat horizontal surface (Fig. 2). For all simulated sizes, the decrease in the production rate for both geometries was observed. The reason for this decrease is the variation in neutron flux near the air-surface interface and the larger escape of particles from the hemispheres than from the flat surface [6]. The production rates calculated for hemispheric geometry are 12% lower for outermost layers than surface production rates calculated for

planar geometry. With depth the difference decreases. In the second type of geometry, the production rates in the top layer are 7% lower and the difference is also decreasing with the depth.

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